International Journal of Electrical and Electronics Engineering Research (IJEEER)
ISSN(P): 2250-155X; ISSN(E): 2278-943X
Vol. 3, Issue 5, Dec 2013, 165-176

MULTI CONVERTER FED UNIFIED POWER QUAITY CONDITIONING SYSTEM

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ABSTRACT

This paper presents a new unified power-quality conditioning system (MC-UPQC), capable of simultaneous compensation for voltage and current in multibus/multifeeder systems. In this configuration, one shunt voltage-source converter (shunt VSC) and two or more series VSCs exist. The system can be applied to adjacent feeders to compensate for supply-voltage and load current imperfections on the main feeder and full compensation of supply voltage imperfections on the other feeders. In the proposed configuration, all converters are connected back to back on the dc side and share a common dc-link capacitor. There fore, power can be transferred from one feeder to adjacent feeders to compensate for sag/swell and interruption. The performance of the proposed configuration has been verified through simulation studies using MATLAB/simulation on a two-bus/two-feeder system and results are presented.

KEYWORDS: Geographical Indications, Marketing Management, Intellectual Property Rights, Product Differentiation, GI Registration

INTRODUCTION

Voltage-source converter based custom power devices are increasingly being used in custom power applications for improving the power quality (PQ) of power distribution systems. Devices such as distribution static Compensator (DSTATCOM) and dynamic voltage restorer (DVR) have already been discussed extensively. A DSTATCOM can compensate for distortion and unbalance in a load such that a balanced sinusoidal current flows through the feeder. It can also regulate the voltage of a distribution bus. A DVR can compensate for voltage sag/swell and distortion in the supply side voltage such that the voltage across a sensitive/critical load terminal is perfectly regulated. A unified power-quality conditioner (UPQC) can perform the functions of both DSTATCOM and DVR .The UPQC consists of two voltage-source converters (VSCs) that are connected to a common dc capacitor. One of the VSCs is connected in series with a distribution feeder, while the other one is connected in shunt with the same feeder. It is possible to connect two VSCs to two different Feeders in a distribution system (IUPQC) and also possible for multibus/multifeeder system (MC-UPQC).

Unified Power Quality Conditioner (UPQC)

Poor power quality in a system could be due to different factors such as voltage sag, voltage swell, voltage outage and over correction of power factor and unacceptable levels of harmonics in the current and voltage. Modern solution for poor power quality is to take advantage of advanced power electronics technology.

Recent research efforts have been made towards utilizing a device called unified power quality conditioner (UPQC) to solve almost all power quality problems. The main purpose of a UPQC is to compensate for supply voltage flicker/imbalance, reactive power, and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore, is expected as one of the most powerful solutions to large capacity loads sensitive to voltage flicker/imbalance.

Unified Power Quality Conditioner (UPQC) for non-linear and voltage sensitive loads has following facilities.

- It eliminates the harmonics in the supply current, thus improves utility current quality for nonlinear loads.
- UPQC provides the VAR requirement of the load, so that the supply voltage and current are always in phase, therefore, no additional power factor correction equipment is necessary.
- UPQC maintains load end voltage at the rated value even in the presence of supply voltage sag.
- The voltage injected by UPQC to maintain the load end voltage at the desired value is taken from the same dc link, thus no additional dc link voltage support is required for the series compensator.

The UPQC consists of two three phase inverters (VSI) connected in cascade in such a manner that one inverter is connected in parallel with the load. Second Inverter is connected in series with the supply voltage through a transformer.

The main purpose of the shunt compensator is to compensate for the reactive power demanded by the load, to eliminate the harmonic components of nonlinear loads in such a way that the source current is sinusoidal and balanced. This equipment is a good solution for the case when the voltage source presents distortion and a harmonic sensitive load is close to a nonlinear load.

The series compensator is operated in PWM voltage controlled mode. It injects voltage in quadrature advance to the supply voltage (current) such that the load end voltage is always maintained at the desired value. The two inverters operate in a coordinated manner.

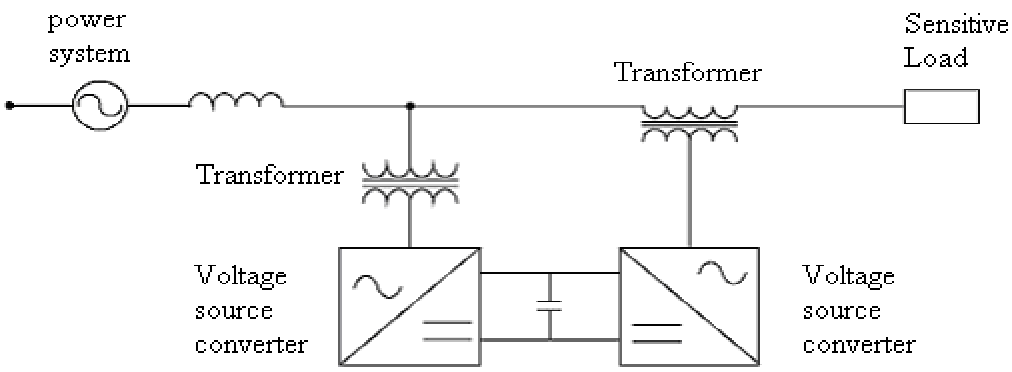


Figure 1: Basic Block Diagram of UPQC

If UPQC is connected between two feeders then the new conditioner developed which is called Interline Unity Power Quality conditioner (IUPQC).This IUPQC comes under series-shunt facts device.

MC-UPQC to Control Power Quality

The series and shunt connected forms the basic principle for the operation of UPQC as it is the back to back connection of the series and shunt connection of the VSCs. If the UPQC device is connected between two feeders fed from different substations then it is called as interline Unified Power Quality Conditioner (IUPQC). If the UPQC device is connected between multibus/multifeeders fed from different substations then it is called as MultiConverter Unified Power Quality Conditioning System (MCUPQC) MCUPQC can improve the power quality by injecting voltage in to any feeder from the DC link Capacitor.

This whole operation is controlled by controlling the three voltage source converters (VSC) connected between the two feeders in the Electrical distribution system.

Circuit Configuration

As shown in this figure 1, two feeders connected to two different substations supply the loads L1 and L2. The MC-UPQC is connected to two buses BUS1 and BUS2 with voltages of u_{t1} and u_{t2}, respectively. The shunt part of the MC-UPQC is also connected to load L1 with a current of i_{l1}. Supply voltages are denoted by u_{s1} and u_{s2} while load voltages are u_{l1} and u_{l2}. Finally, feeder currents are denoted by i_{s1} and i_{s2} and load currents are i_{l1} and i_{l2}.

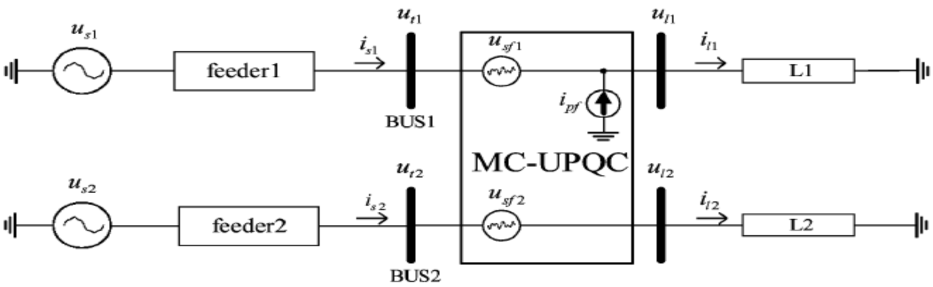


Figure 2: Single-Line Diagram of a Distribution System with an MC-UPQC

Bus voltages u_{t1} and u_{t2} are distorted and may be subjected to sag/swell. The load L1 is a nonlinear/sensitive load which needs a pure sinusoidal voltage for proper operation while its current is non-sinusoidal and contains harmonics. The load L2 is a sensitive/critical load which needs a purely sinusoidal voltage and must be fully protected against distortion, sag/swell, and interruption. These types of loads primarily include production industries and critical service providers, such as medical centers, airports, or broadcasting centers where voltage interruption can result in severe economical losses or human damages.

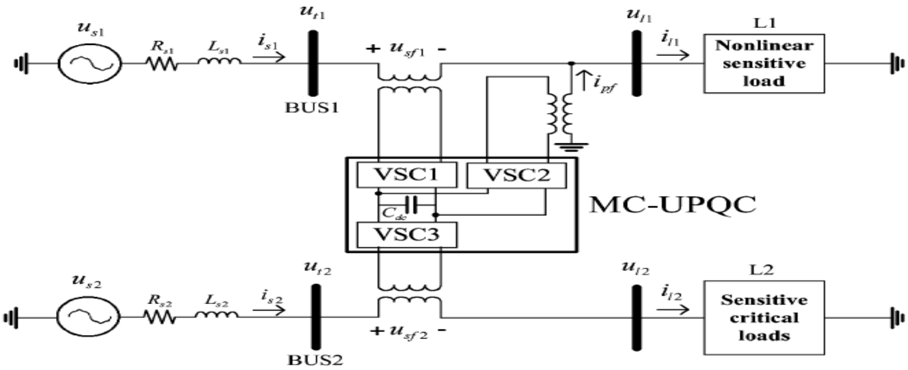


Figure 3: Typical MC-UPQC Connected in Distribution System

Control and Operation of MC-UPQC

As shown in Figure the MC-UPQC consists of two series VSCs and one shunt VSC which are controlled independently. The switching control strategy for series VSCs and the shunt VSC are selected to be sinusoidal pulse width-modulation (SPWM) voltage control and hysteresis current control, respectively. Details of the control algorithm, which are based on the – method [12], will be discussed later.

Shunt-VSC: Functions of the shunt-VSC are:

- To compensate for the reactive component of load L1 current;
- To compensate for the harmonic components of load L1 current;
- To regulate the voltage of the common dc-link capacitor.

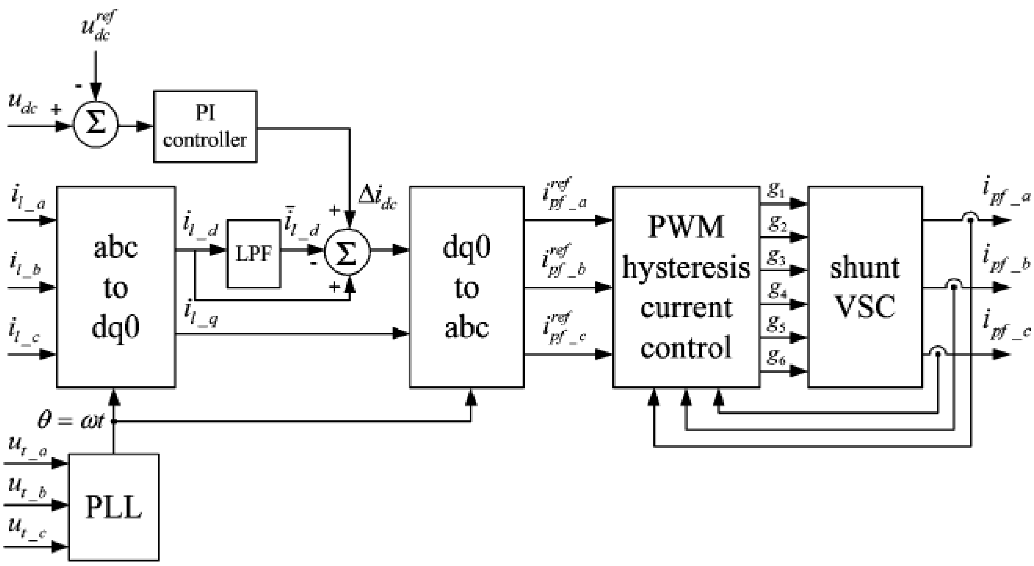


Figure 4: Control Block Diagram of the Shunt VSC

Figure shows the control block diagram for the shunt VSC. The measured load current ($i_{l\text{-}abc}$) is transformed into the synchronous dqo reference frame by using

$$\boldsymbol{i_{l\_dq0} = T_{abc}^{dq0}\, i_{l\_abc}}$$

Where the transformation matrix is shown in (2),

$$T_{abc}^{dq0} = 2/3 \begin{pmatrix} \cos(\omega t) & \cos(\omega t - 120^\circ) & \cos(\omega t + 120^\circ) \\ -\sin(\omega t) & -\sin(\omega t - 120^\circ) & -\sin(\omega t + 120^\circ) \\ 1/2 & 1/2 & 1/2 \end{pmatrix}$$

By this transform, the fundamental positive-sequence component, which is transformed into dc quantities in the axes, can be easily extracted by low-pass filters (LPFs). Also, all harmonic components are transformed into ac quantities with a fundamental frequency shift

$$\boldsymbol{i_{l\text{-}d} = i_{l\_d} + i_{l\_d}}$$

$$\boldsymbol{i_{l\_d} = i_{l\_q} + i_{l\_q}}$$

Where $i_{l\text{-}d}$ and $i_{l\text{-}q}$ are d-q components of load current, i_{l_d} and i_{l_q} are dc components, and $il_{\_d}$ and i_{l_d} are the ac components of $i_{l\text{-}d,}$ and $i_{l\text{-}q.}$

If i_s is the feeder current and $i_{p\,f}$ is the shunt VSC current and knowing $i_s = i_l - i_{pf}$, then d–q components of the shunt VSC reference current are defined as follows:

$$\boldsymbol{i_{p\,f\_d}^{ref} = i_{l\_d}}$$

$$\boldsymbol{i_{p\,f\_d}^{ref} = i_{l\_q}}$$

Consequently, the d–q components of the feeder current are

$$\boldsymbol{i_{s\_d} = i_{l\_d}}$$

$$\boldsymbol{i_{s\_q} = 0.}$$

This means that there are no harmonic and reactive components in the feeder current. Switching losses cause the dc-link capacitor voltage to decrease. Other disturbances, such as the sudden variation of load, can also affect the dc link. In order to regulate the dc-link capacitor voltage, a proportional–integral (PI) controller is used as shown in Figure. The input of the PI controller is the error between the actual capacitor voltage (u_{dc}) and its reference value ($u_{dc}^{\ ref}$).

The output of the PI controller (i.e., delta i_{dc}) is added to the component of the shunt-VSC reference current to form a new reference current as follows:

$$\begin{cases} i_{pf\_d}^{\ ref} = i_{l\_d} + \Delta i_{dc} \\ i_{pf\_q}^{\ ref} = i_{l\_q} \end{cases}$$

As shown in Figure 4, the reference current in (6.11) is then transformed back into the *abc* reference frame. By using PWM hysteresis current control, the output-compensating currents in each phase are obtained.

$$i_{pf\_abc}^{\ ref} = T_{dq0}^{\ abc}\, i_{pf\_dq0}^{\ ref};\ (T_{dq0}^{\ abc} = T_{abc}dq0^{-1})$$

***Series-VSC**:* Functions of the series VSCs in each feeder are:

- To mitigate voltage sag and swell;
- To compensate for voltage distortions, such as harmonics;
- To compensate for interruptions (in Feeder 2 only).

The control block diagram of each series VSC is shown in Figure 5. The bus voltage ($u_{t\text{-}abc}$) is detected and then transformed into the synchronous dq0 reference frame using

$$\mathbf{u}_{t\_dq0} = \mathbf{T}_{abc}^{\ dq0}\, \mathbf{u}_{t\_abc} = \mathbf{u}_{t1p} + \mathbf{u}_{t1n} + \mathbf{u}_{th}$$

Where

$$\begin{cases} u_{t1p} = [u_{t1p\_d} \quad u_{t1p\_q} \quad 0]^T \\ u_{t1n} = [u_{t1n\_d} \quad u_{t1n\_q} \quad 0]^T \\ u_{t10} = [0 \quad 0 \quad u_{00}]^T \\ u_{\mathrm{th}} = [u_{th\_d} \quad u_{th\_q} \quad u_{th\_0}]^T \end{cases}$$

u_{t1p}, u_{t1n} and u_{t10} are fundamental frequency positive-, negative-, and zero-sequence components, respectively, and u_{th} is the harmonic component of the bus voltage.

According to control objectives of the MC-UPQC, the load voltage should be kept sinusoidal with constant amplitude even if the bus voltage is disturbed. Therefore, the expected load voltage in the synchronous dqo reference frame ($u^{exp}{}_{l\text{-}dqo}$) only has one value

$$u_{l\_dq0}^{\ exp} = T_{abc}^{\ dq0}\, u_{l\_abc}^{\ exp} = \begin{pmatrix} U_m \\ 0 \\ 0 \end{pmatrix}$$

Where the load voltage in the *abc* reference frame ($u_{exp\ l\text{-}abc}$) is

$$u_{l\_dq0}^{exp} = \begin{pmatrix} U_m \cos(\omega t) \\ U_m \cos(\omega t - 120°) \\ U_m \cos(\omega t + 120°) \end{pmatrix}$$

The compensating reference voltage in the synchronous dqo reference frame ($u^{exp}{}_{l\text{-}dqo}$) is defined as

$$\mathbf{u_{sf\_dq0}^{ref} = u_{t\_dq0} - u_{l\_dq0}^{exp}}$$

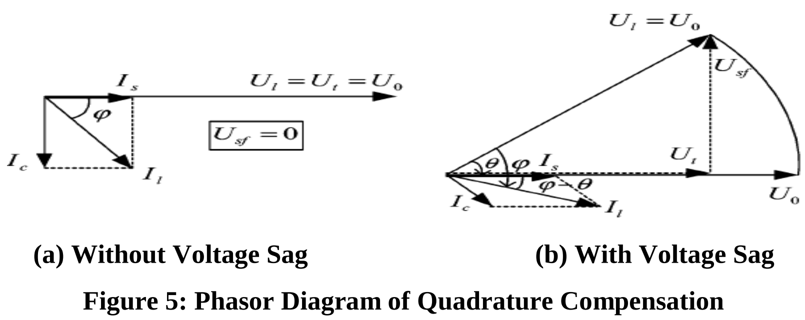
This means $u_{t1p\text{-}d}$ in (12) should be maintained at $\mathbf{U}_m$ while all other unwanted components must be eliminated. The compensating reference voltage in (6.17) is then transformed back into the abc reference frame. By using an improved SPWM voltage control technique (sine PWM control with minor loop feedback), the output compensation voltage of the series VSC can be obtained.

Power Rating Analysis of the MC-UPQC

The power rating of the MC-UPQC is an important factor in terms of cost. Before calculation of the power rating of each VSC in the MC UPQC structure, two models of a UPQC are analyzed and the best model which requires the minimum power rating is considered. All voltage and current phasors used in this section are phase quantities at the fundamental frequency.

There are two models for a UPQC-quadrature compensation (UPQC-Q) and inphase compensation (UPQC-P). In the quadrature compensation scheme, the injected voltage by the series- VSC maintains a quadrature advance relationship with the supply current so that no real power is consumed by the series VSC at steady state. This is a significant advantage when UPQC mitigates sag conditions. The series VSC also shares the volt-ampere reactive (VAR) of the load along with the shunt-VSC, reducing the power rating of the shunt-VSC.

Figure shows the phasor diagram of this scheme under a typical load power factor condition with and without voltage sag. When the bus voltage is at the desired value, (U_t=U_l=$U_{0)}$ the series-injected voltage (U_{sf}) is zero Figure. The shunt VSC injects the reactive component of load current, resulting in unity input-power factor. Furthermore, the shunt VSC compensates for not only the reactive component, but also the harmonic components of the load current. For sag compensation in this model, the quadrature series voltage injection is needed as shown in Figure 6(b). The shunt VSC injects I_c in such a way that the active power requirement of the load is only drawn from the utility which results in a unity input-power factor.



(a) Without Voltage Sag **(b) With Voltage Sag**

Figure 5: Phasor Diagram of Quadrature Compensation

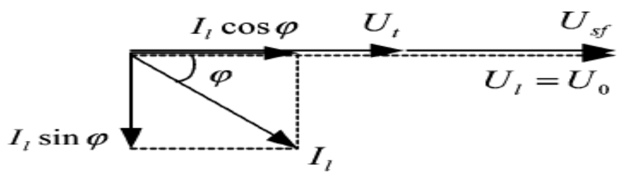


Figure 6: Phasor Diagram of Inphase Compensation (Supply Voltage Sag)

In an inphase compensation scheme, the injected voltage is inphase with the supply voltage when the supply is balanced. By virtue of inphase injection, series VSC will mitigate the voltage sag condition by minimum injected voltage. The phasor diagram of Figure 7 explains the operation of this scheme in case of voltage sag.

A comparison between in-phase (UPQC-P) and quadrature (UPQC-Q) models is made for different sag conditions and load power factors. It is shown that the power rating of the shunt-VSC in the UPQC-Q model is lower than that of the UPQC-P, and the power rating of the series-VSC in the UPQC-P model is lower than that of the UPQC-Q for a power factor of less than or equal to 0.9.

Also, it is shown that the total power rating of UPQC-Q is lower than that of UPQC-P where the VAR demand of the load is high.

As discussed in Section II, the power needed for interruption compensation in Feeder2 must be supplied through the shunt VSC in Feeder1 and the series VSC in Feeder 2. This implies that power ratings of these VSCs are greater than that of the series one in Feeder 1. If quadrature compensation in Feeder1 and in-phase compensation in Feeder 2 are selected, then the power rating of the shunt VSC and the series VSC (in Feeder2) will be reduced. This is an important criterion for practical applications.

Based on the aforementioned discussion, the power-rating calculation for the MC-UPQC is carried out on the basis of the linear load at the fundamental frequency. The parameters in Figure 6 are corrected by adding suffix “1,” indicating Feeder1, and the parameters in Figure 7 are corrected by adding suffix “2,” indicating Feeder2. As shown in Figures 6 and 7, load voltages in both feeders are kept constant at U_0 regardless of bus voltages variation, and the load currents in both feeders are assumed to be constant at their rated values (i.e., I_{01} and I_{02}, respectively)

$$\begin{cases} U_{l1} = U_{l2} = U_0 \\ I_{l1} = I_{01}, \\ I_{l2} = I_{02} \end{cases}$$

The load power factors in Feeder1 and Feeder2 are assumed to be $\cos\varphi_1$ and $\cos\varphi_2$ and the per-unit sags, which must be compensated in Feeder1 and Feeder2, are supposed to be x_1 and x_2, respectively.

If the MC-UPQC is lossless, the active power demand supplied by Feeder1 consists of two parts:

- The active power demand of load in Feeder 1;
- The active power demand for sag and interruption compensation in Feeder 2.

Thus, Feeder1 current (I_{s1}) can be found as

$$U_{t1} I_{s1} = U_{l1} I_{l1} \cos Ø_1 + U_{sf2} I_{l2} \cos Ø2$$

$$(1-x_1) U_0 I_{s1} = U_0 I_{01} \cos Ø_1 + x_2 U_0 I_{02} \cos Ø2$$

$$(1-x_1) I_{s1} = I_{01} \cos Ø_1 + x_2 I_{02} \cos Ø2$$

$$I_{s1} = \frac{I_{01}\cos\varphi_1}{(1-x_1)} + \frac{x_2 I_{02}\cos\varphi_2}{(1-x_1)}.$$

From Figure the voltage injected by the series VSC in Feeder1 can be written as in (6.24) and, thus, the power rating of this converter (S_{VSC1}) can be calculated as

$$\mathbf{U_{sf1} = U_{t1} \tan\theta = U_0 (1-x_1) \tan\theta}$$

$$S_{\mathrm{VSC1}} = 3U_{\mathrm{sf1}} I_{s1} = 3U_0(1-x_1)\tan\theta \times \left(\frac{I_{01}\cos\varphi_1}{1-x_1} + \frac{x_2 I_{02}\cos\varphi_2}{1-x_1}\right)$$

The shunt VSC current is divided into two parts.

- The first part (i.e., I_{c1}) compensates for the reactive component (and harmonic components) of Feeder1 current and can be calculated from Figure 6 as

$$I_{c1} = \sqrt{I_{l1}^2 + I_{s1}^2 - 2I_{l1} I_{s1} \cos(\varphi_1 - \theta)} = \sqrt{I_{01}^2 + I_{s1}^2 - 2I_{01} I_{s1} \cos(\varphi_1 - \theta)}$$

where I_{s1} is calculated in (6.23). This part of the shunt VSC current only exchanges reactive power (Q) with the system.

- The second part provides the real power (P), which is needed for sag or interruption compensation in Feeder 2. Therefore, the power rating of the shunt VSC can be calculated as

$$S_{VSC2} = 3U_{t1} I_{pf} = 3\sqrt{Q^2 + P^2} = 3\sqrt{(U_{t1} I_{c1})^2 + (U_{sf2} I_{l2} \cos\varphi_2)^2} = 3U_0 \sqrt{I_{c1}^2 + (x_2 I_{02} \cos\varphi_2)^2}$$

Where I_{c1} is calculated.

Finally, the power rating of the series-VSC in Feeder2 can be calculated by for the worst-case scenario (i.e., interruption compensation), one must consider $x_2=1$. Therefore,

$$\mathbf{S_{VSC3} = 3U_{sf} I_{l2}} = 3x_2 U_0 I_{02}$$

SIMULATION AND RESULTS

MATLAB/SIMULINK Model of Distribution System without MC-UPQC

This configuration presents a new connection for a UPQC called Multi-Converter UPQC (MC-UPQC). Two feeders called Feeder-1 and Feeder-2, which are connected to two different substations, supply the system loads L-1 and L-2. The purpose of the MC-UPQC is to hold the voltages and constant against voltage sag/swell, temporary interruption in either of the two feeders. It has been demonstrated that the MC-UPQC can absorb power from one feeder (say Feeder-1) to hold constant in case of a sag in the voltage. This can be accomplished as the two VSCs are supplied by a common dc capacitor. The performance of the MC-UPQC has been evaluated through simulation studies using MATLAB/SIMULINK.

Figure 7 shows the distribution system without MC-UPQC is simulated in MATLAB/SIMULINK. Here two blocks are considered one is source and second is load. Three phase AC voltage source is used in MATLAB/SIMULINK. This source is connected to three phase RL branch which gives the line resistance and reactance. Here the supply is

connected to the load L-1.and again the load L-1 is assumed to have a non-linear part (L-1). Here Bridge operation is considered. In bridge operation because of continuous switching operation of the switches harmonics are developed in both supply side and load side.

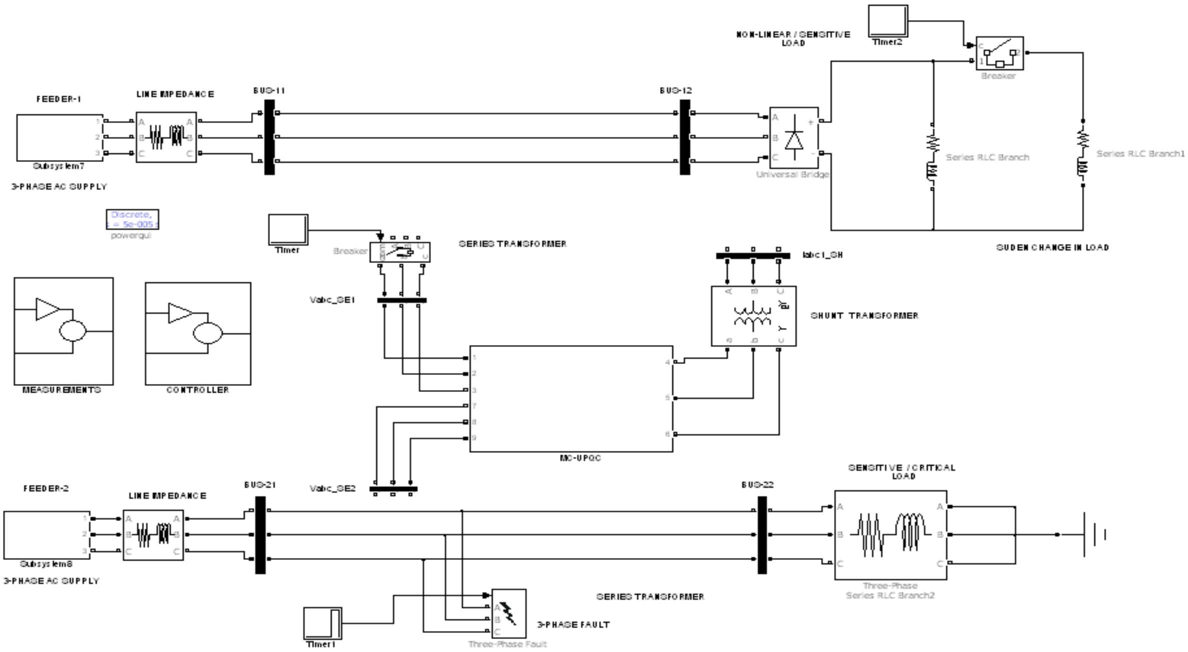


Figure 7: Simulink Model of Distribution System without MC-UPQC

Due to presence of the non-linear load the system response gives poor power quality. This can be observed by seeing the response of the distribution system.

Figure 7 shows the three phase line voltage across non-linear without MC-UPQC is considered, here because of the non-linear condition; all the three phase voltages are distorted and maintaining poor power quality. When MC-UPQC is connected to the system, there is no matter of introducing capacitive storage voltage in to the line, so the waveforms are distorted.

Figure 8 shows three phase voltage across non-linear load without MCUPQC. Due to continuous switching operation of the thyristors, the voltage across the bridge circuit are distorted. Figure 8 shows three phase line current passing in to the load. These are also unbalanced. So the main objective of MC-UPQC is to regulate these distorted unbalanced voltages and currents.

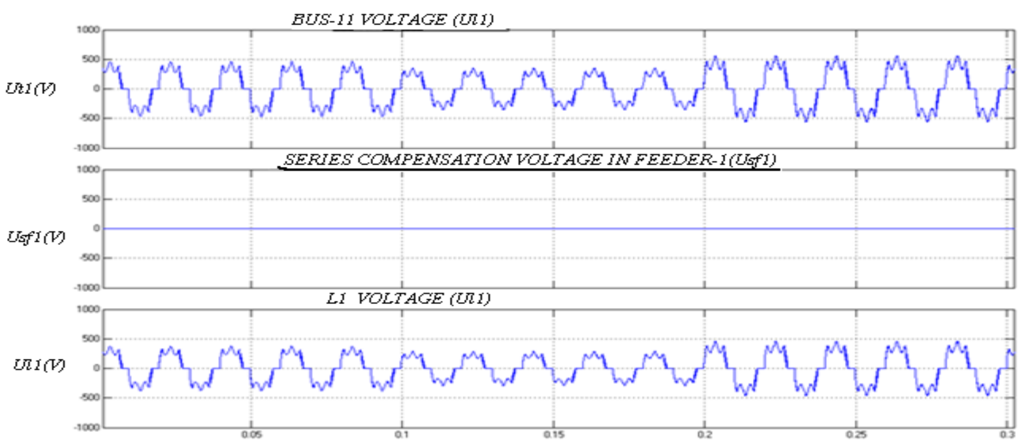


Figure 8: BUS1 Voltage, Series Compensating Voltage, and Load Voltage in Feeder1 without MC-UPQC

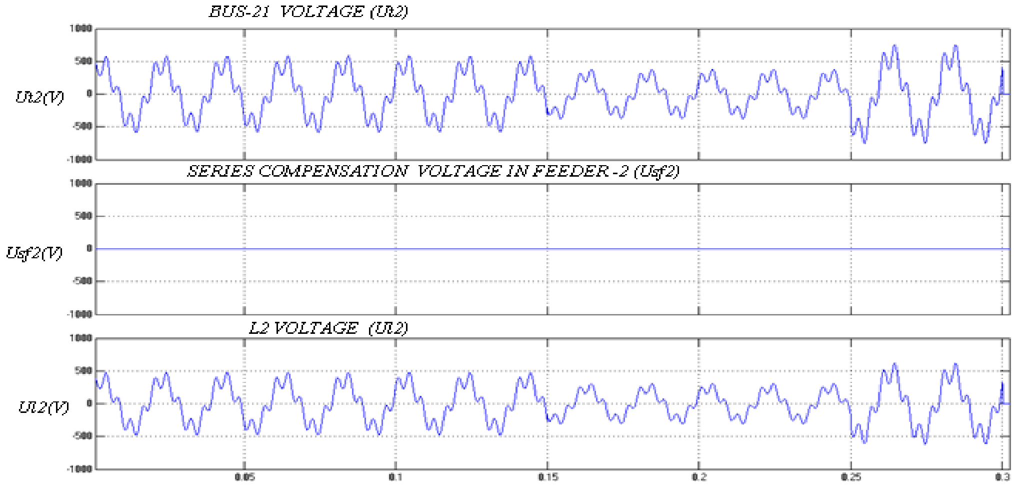


Figure 9: BUS2 Voltage, Series Compensating Voltage, and Load Voltage in Feeder 2 without MC-UPQC

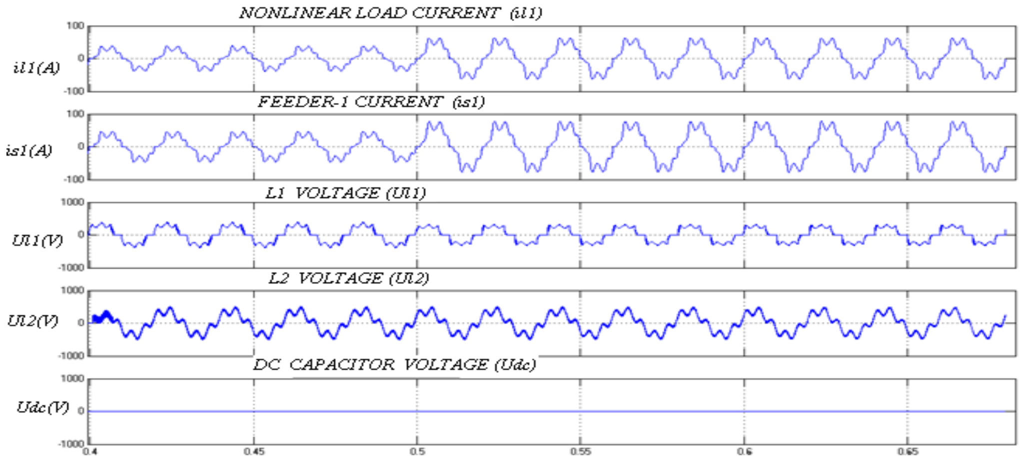


Figure 10: Simulation Results for Load Change: Nonlinear Load Current, Feeder 1 Current, Load L1 Voltage, Load L2 Voltage, and Dc-Link Capacitor Voltage without MC-UPQC

MATLAB/SIMULINK Model of Distribution System with MC-UPQC

In the proposed configuration VSC1 is connected in series with bus 1 and VSC2 is connected in parallel with load end of feeder 1, VSC3 is connected in series with bus 2 at the feeder 2 end. Each of the three VSCs in Figure 10 is related by three phase converter with commutation reactor and high pass filter as shown in Figure 11. The commutation reactor (L_f) and high pass output filter (R_f, C_f) are connected to prevent the flow of switching harmonics into the power supply.

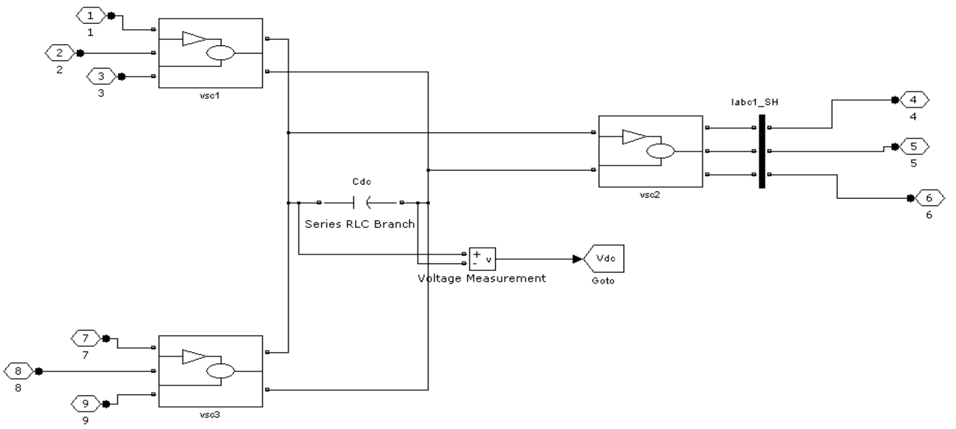


Figure 11: Simulink Model of MC-UPQC Sub System

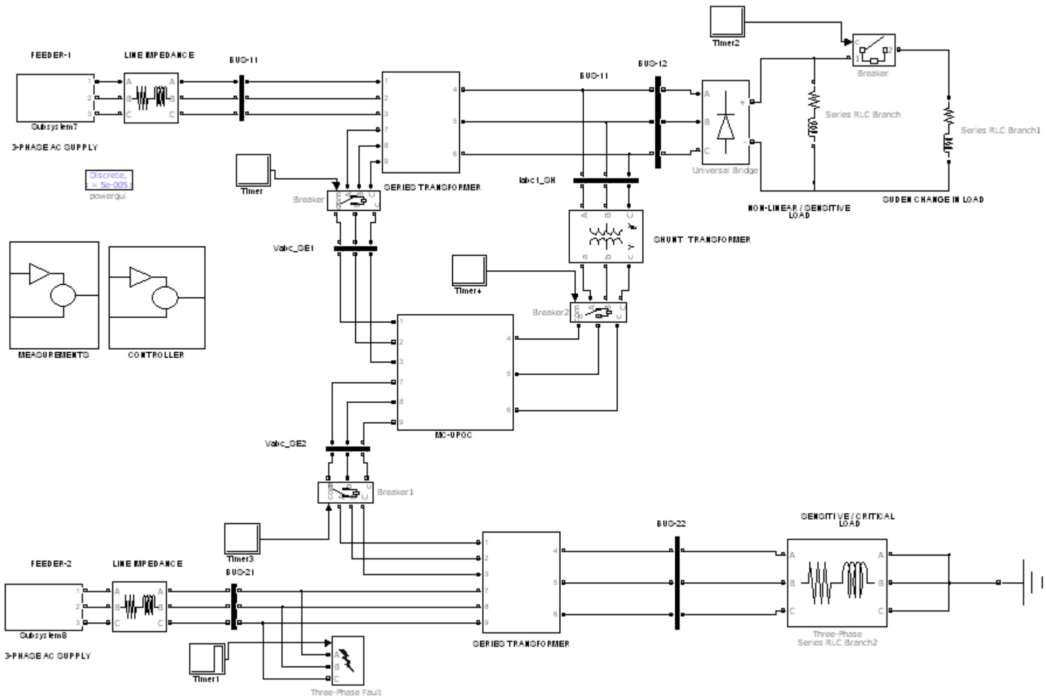


Figure 12: Simulink Model of Distribution System with MC-UPQC

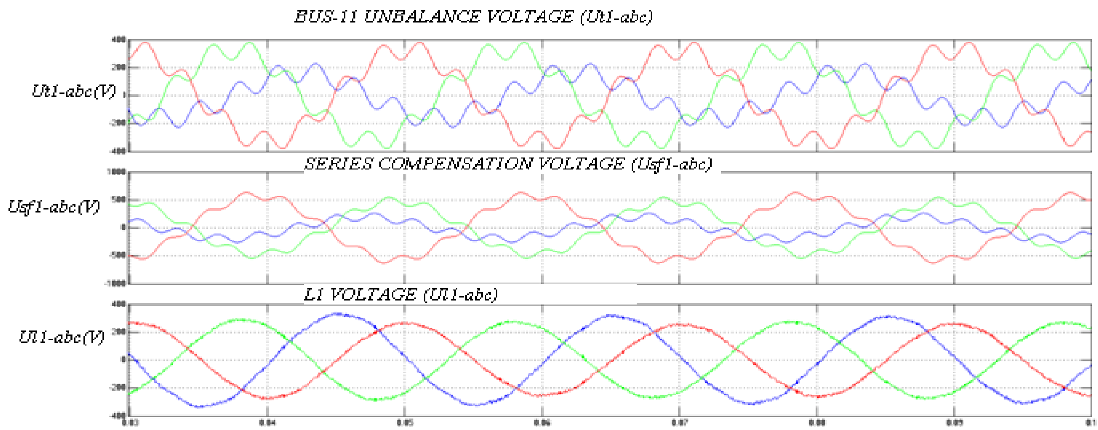


Figure 13: BUS1 Voltage, Series Compensating Voltage, and Load Voltage in Feeder1 Under Unbalanced Source Voltage with MC-UPQC

CONCLUSIONS

Compared to a conventional UPQC, the proposed topology is capable of fully protecting critical and sensitive loads against distortions, sags/swell, and interruption in two-feeder systems. The idea can be theoretically extended to multibus/multifeeder systems by adding more series VSCs. The performance of the MC-UPQC is evaluated under various disturbance conditions and it is shown that the proposed MC-UPQC offers the following advantages:

- Power transfer between two adjacent feeders for sag/swell and interruption compensation;
- Compensation for interruptions without the need for a battery storage system and, consequently, without storage capacity limitation;
- Sharing power compensation capabilities between two adjacent feeders which are not connected.

From above discussion, it has been observed that an MC-UPQC is able to protect the distribution system from various disturbances occurring either in Feeder-1 or in Feeder-2. As far as the common dc link voltage is at the reasonable level, the device works satisfactorily. The angle controller ensures that the real power is drawn from Feeder-1 to hold the dc link voltage constant.

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